NUTRITION in EXERCISE and SPORT
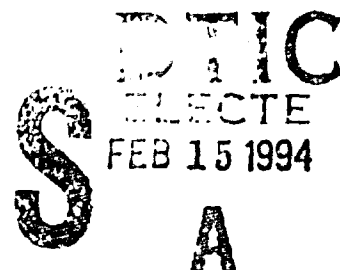
_____ 2nd Edition

Editors

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Chapter 19

NUTRITION AND PERFORMANCE AT ENVIRONMENTAL EXTREMES*

_____ Eldon W. Askew

CONTENTS

I. INTRODUCTION

Humans are remarkably adaptive animals, having learned to survive and even thrive in environments outside their normal "comfort" zone. Man accomplishes these adaptations through metabolic and behavioral changes. Environments that threaten to overwhelm the ability of man to adjust his metabolism and/or change behavioral strategies have been referred to as "hostile" environments.[1] This terminology is a misnomer, since man can function safely and effectively in extremes of environments, provided adequate behavioral precautions (e.g., clothing, shelter, food, water) are taken. The environment becomes "hostile" only when man has entered it unprepared or the environment is so severe that it threatens to surpass man's ability to adapt or respond appropriately to its challenges.

Although man is a remarkably adaptive animal, he has limitations. One of these limitations is homeothermy. Shephard[2] described mankind as being "... metabolic hostages of the homeothermic condition." This means regardless of the environmental temperatures, man must defend the normal body temperature of 37°C (98.5°F) within a relative narrow range of temperatures. We have several physiologic defense mechanisms at our disposal (e.g., shivering, sweating, vasodilation, or vasoconstriction) to help maintain homeothermy. When the capability of these defense mechanisms is exceeded and body core temperature drops below 35°C (95°F) or rises above 41°C (106°F), the human body functions at such reduced efficiency that both physical and mental performance deteriorates rapidly.[2,3] Left unchecked, hypothermia and hyperthermia can be life threatening. Hypoxia associated with high-altitude environments can also impose severe restrictions on physical performance and jeopardize survival.[4] High altitudes are usually accompanied by cold temperatures, compounding environmental stress and metabolic challenge.

The body's metabolic response to heat, cold, and hypoxia can also be impaired by inadequate nutrition. This is depicted schematically in Figure 1. Appetite and thirst responses are frequently inappropriate in these environmental extremes, leading to inadequate calorie or fluid intakes. The availability of water and food is often limited due to logistical constraints. Backpackers, mountaineers, and explorers are usually limited to the food they can carry with them in their packs. The weight of these packs is critical; often food and water are sacrificed to make room for essential equipment, clothing, and gear. Inadequate dietary energy (particularly carbohydrate and protein) can result in glycogen depletion and loss of lean body mass. This, in turn can result in impaired thermoregulation and impaired muscle strength, coordination, and endurance. Inadequate fluid intakes coupled with increased sweating, loss of lung-humidified air to an arid environment or altitude, or cold-induced diuresis can lead to dehydration and compromised thermoregulation and endurance. The usual increased energy and fluid demands for work in environmental extremes can be exacerbated by anorexia (hypophagia) and inappropriate thirst response (hypodipsia). The effects of hypophagia and hypodipsia can be further complicated by the general lack of food and water in cold, desert, or high-altitude settings. Negative energy and fluid balances can combine to cause substantial decreases in physical performance capacities.[5-9]

Expeditionary or recreational outdoor activities are frequently conducted in hot, cold, high-altitude, or rugged-terrain environments. Mountaineering, cross-country skiing, snowshoeing, sledging, and backpacking can be as physically demanding as more conventional sporting events, plus there is an added element of danger. The wilderness is much less forgiving of mistakes than a more "civilized" environment where medical care is just minutes away. A miscalculation of physical ability or inadequate preparation can be life threatening in environmental extremes. Proper education, planning, preparation, equipment, and training are essential for work in the heat, cold, and high altitudes.

Proper nutrition is an often-overlooked but critical component of effective work under these conditions. The information in this chapter may be useful to individuals planning

CASCADE EFFECT OF ENVIRONMENTAL EXTREMES ON WORK PERFORMANCE

INCREASED ENERGY REQUIREMENT ◄──┐┌──► INCREASED WATER REQUIREMENT ──┐

HYPOPHAGIA ◄── EXTREME ENVIRONMENTS ──► HYPODIPSIA

DECREASED FOOD AVAILABILITY   DECREASED FLUID AVAILABILITY

NEGATIVE ENERGY BALANCE   DEHYDRATION

CONSEQUENCES
* IMPAIRED THERMOREGULATION
* KETOSIS
* PERTURBED ACID-BASE BALANCE
* DEPLETED MUSCLE GLYCOGEN
* DETERIORATION OF FINE MOTOR COORDINATION
* DIMINISHED WORK CAPACITY

FIGURE 1. Schematic representation of the influence of extreme environments upon energy balance, hydration status, and resultant consequences. This generalized diagram illustrates the influence of heat, cold, and/or high altitude on the cascade of events that can lead to physiological consequences and impaired performance.

TABLE 1 Energy Requirements for Physical Activity in Temperate, Cold, and Hot Environments

Physical activity	Environment		
	Temperate[a]	Cold (kcal/kg BW)	Hot
Light	32–44	35–46	40–54
Moderate	45–52	47–55	55–61
Heavy	53–63	56–68	62–75

[a] Altitude energy requirements are similar to temperate.

From Consolazio, C. F., *Army Research and Development Newsmagazine*, November 1966, p. 24. With permission.

nutritional support for work in hot (greater than 30°C/86°F), cold (less than 0°C/32°F), or at high-altitude (greater than 3050 m/10,000 ft elevation) environments.

II. ENVIRONMENT, METABOLISM, AND NUTRIENT REQUIREMENTS

Extremes in the external environment can influence the requirements for certain nutrients,[10-13] and may have implications for people who live or recreate, and athletes who train or compete, under these conditions.[14,15] The need for additional vitamins and minerals may be influenced by certain environments, but the two nutrients most often in short supply are energy (more specifically carbohydrate) and water. Achieving energy balance is often difficult, for the reasons illustrated in Figure 1. Consolazio[16] estimated energy requirements for work in temperate, hot, cold, and high-altitude environments. These guidelines are shown Table 1.

Athletes can sustain a high-level work output only when they manage to maintain energy balance.[17] Work is not necessarily severely impaired following hypocaloric diets.[8] More commonly, the upper limit of power output during endurance exercise with intensity greater than 60% VO_2 max is limited[17] during energy deficiency and the ability of muscles to resist fatigue may be reduced.[18,19] Energy (more specifically carbohydrate) deficiency results in reduced muscle glycogen stores[15] and an increased reliance upon body fat stores to support work output.[5]

Trekkers often take along high-fat foods to increase the energy density of their diets. Under most circumstances, relying upon dietary or body fat stores to meet energy requirements in high energy expenditure activities in the heat, cold, or at high altitude is not advisable. Given a sufficient period for adaptation, muscles are able to shift their substrate utilization from carbohydrate to lipid.[20] This permits maintenance of only a relatively low-intensity work load. High-fat diets are not generally recommended for environmental extremes where high power outputs are necessary (due to the requirement of carbohydrate by muscles for maximum power output).[17] High-fat diets may not be well tolerated (reduced appetite appeal or digestibility) in hot or high-altitude settings; however, they seem to be tolerated relatively well in cold environments close to sea level.

Exposures to extreme heat, cold, or high altitude alters muscle metabolism by a variety of factors, including muscle temperature, pH, O_2 tension, as well as cofactor and substrate availability.[21] As an example, unacclimatized individuals generally exhibit greater muscle glycogen breakdown, glycolytic flux, and lactate accumulation in extreme environments compared to temperate conditions at sea level.[21] (The "lactate paradox" of diminished blood lactate following *maximal* exercise at altitude compared to sea level is an exception to this generalization.[22])

III. NUTRIENT REQUIREMENTS FOR WORK IN HOT ENVIRONMENTS

Adequate fluid replacement overshadows all other considerations of nutrient requirements for work in a hot environment. Drinking adequate water for work in the heat prevents dehydration, heat illness, and reduced performance.[6,23] Heat acclimation can reduce sodium requirements for work in the heat[7] but water requirements remain relatively unaffected.[6,24] Thirst is a poor indicator of hydration status.[23] Intense thirst is usually noticed at 5 to 6% body weight loss due to dehydration. By this time physical performance is compromised. Vague discomfort, lethargy, weariness, sleepiness, and apathy, as well as elevated body core temperature, heart rate, and muscular fatigue are noted as body water loss reaches the 3 to 5% level. The magnitude of the increase in body core temperature and heart rate elicited by dehydrating exercise is linearly related to the level of body water deficit.[25]

Severe hypohydration can lead to decreased blood volume and increased plasma osmolality, which can decrease sweating and heat dissipation.[25,26] Eighty percent of the energy metabolized during exercise in a hot environment is liberated as heat (20% is utilized for mechanical work) and 80 to 90% of heat dissipation during exercise in a hot-dry environment is accomplished by the evaporation of sweat.[27,28] Water consumed during exercise in the heat can move to the sweat glands within 9 to 18 min of ingestion, where it is available for cooling the body.[27] Each milliliter of sweat evaporated from the skin will lead to a heat loss or dissipation of approximately 0.6 kcal.[28] Sweat rates are highly variable between individuals, but can reach 2 l/h for prolonged time periods.[29] Dehydration depends in large part upon sweat loss, which is in turn determined by exercise intensity and duration, as well as environmental factors such as temperature, solar load, wind speed, and relative humidity and clothing. The influence of these factors on water requirements for work in the heat is illustrated in Table 2.[30,31]

It is important to note under certain environmental conditions a 10°F increase in temperature can cause a 50 to 60% increase in water requirements at *rest*. Superimposing an increased

TABLE 2 Water Requirements (l/h) for Rest and Work in the Heat as Influenced by Solar Load and Temperature

Temperature and relative humidity (°F @ % rh)	Indoors (no solar load)				Outdoors (clear sky)			
	Rest	Light	Medium	Heavy	Rest	Light	Medium	Heavy
85 @ 50	0.2	0.5	1.0	1.5	0.5	0.9	1.3	1.8
96 @ 50	0.3	0.9	1.3	1.9	0.8	1.2	1.7	2.0
105 @ 30	0.6	1.0	1.5	2.0	0.9	1.3	1.9	2.0
115 @ 20	0.8	1.2	1.7	2.0	1.1	1.5	2.0	2.0
120 @ 20	0.9	1.3	1.9	2.0	1.3	1.7	2.0	2.0

Note: The values for water requirements in l/h were calculated according to the prediction model of Shapiro et al.[30] by L. A. Stroschein, Biophysics and Biomedical Modeling Division, U.S. Army Research Institute of Environmental Medicine, Natick, MA. The following conditions were assumed in these calculations: clothing, tropical fatigues; heat-acclimatized subjects; wind speed 2 m/s.

work load at high temperatures greatly increases fluid requirements. The solar load, relative humidity, clothing, wind speed, and prior acclimation to heat all interact in determining sweat rates, insensible water loss, and water requirements at any given workload.[31] Consolazio[16] recommended up to 12 l of water per day for soldiers engaged in heavy physical activity in 100°F weather. While this level of water intake may be necessary to replenish fluid losses in a hot environment, it may be difficult to ingest such a large volume. As an example, it would be necessary to consume 1 l of water upon arising in the morning, 1 l with each of three meals and 1 l for each hour during an 8-h work day to achieve a daily intake of 12 l. This rate of fluid consumption is possible, but requires conscious effort. The U.S. military refers to planned or programmed water drinking as "water discipline"[32] and credits this doctrine for the relatively low incidence of U.S. heat casualties in the 1990–1991 Desert War in Iraq and Kuwait.

As a general rule, salt supplements are not necessary for work in the heat unless water is available but food is not.[33] Since the typical daily American diet contains 6 to 18 g of NaCl,[34] replacement of sodium lost during exercise in the heat can usually be met by consuming normally salted food in proportion to caloric requirements.[16,33] This is usually an adequate amount of sodium to replace that lost in sweat in a hot environment. Armstrong et al.[35] demonstrated that humans could successfully acclimate to work in the heat on as little as 6 g of NaCl/d although higher levels of sodium intake (8 g) reduced some of the adverse symptoms asssociated with this period of heat acclimation.

Sodium losses can, however, be quite high at sustained moderate work rates in a hot environment. Sweat losses amounting to 12 l/24 h can result in the loss of 11,000 to 16,500 mg of Na$^+$ per day.[36] Under these conditions sodium replacement will require liberal salting of food, drinking water that contains 1.0 g of NaCl/l[16] (390 mg Na$^+$), or consuming sodium-containing "sports" beverages in place of a portion of the 12 l/d water requirement. Sodium supplementation should be given consideration only when fluid replacement is adequate. Barr et al.[37] found that sodium replacement during exercise in the heat does not appear necessary for moderate-intensity work up to 6 h duration. Excess salt consumption can place an added burden on water requirements in all environments (Figure 2).[38] In addition to increasing water requirements, high salt intake (without adequate water intake) can elevate plasma osmolality, which can lead to decreased sweating and as a result, increase thermal strain during work.[24]

Although water and sodium replenishment are the primary nutrients of concern in a hot environment, consideration should also be given to providing adequate energy. Food and
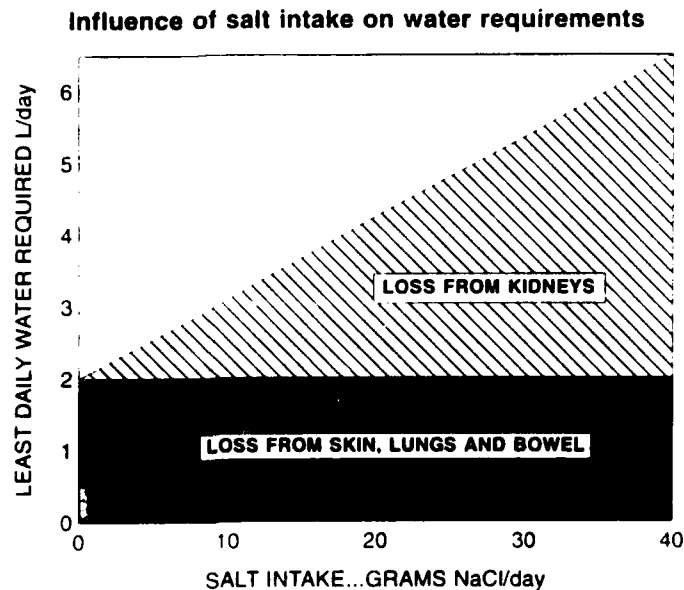
Influence of salt intake on water requirements

FIGURE 2. Estimated minimum daily water requirement of a sedentary man weighing 70 kg at an ambient temperature of 75°F, relative humidity of 19%, consuming 0 to 30 g of NaCl/day. (From Baker, E. M., Plough, I. C., and Allen, T. H., *Am. J. Clin. Nutr.*, 12, 394, 1963. With permission.)

water intakes are closely related; food intake is reduced during water deprivation and water intake is reduced during starvation.[39] Energy requirements for work in the heat may be elevated 0.5% for each 1°F increase as the ambient temperature increases from 86 to 104°F.[16] Below temperatures of 86°F (30°C) temperature has little influence on energy requirements until cold temperatures (requiring additional clothing to prevent excessive heat loss) are reached. The relatively small increase in energy requirements for work at high temperatures is believed to be attributable to increased cardiovascular work needed to dissipate heat, increased sweat gland activity, and metabolic rate. Consolazio et al.[40] found approximately a 10% increase in metabolic cost for work at 100°F compared to work at 70°F. Sawka et al.[41] subsequently demonstrated that heat acclimation can lower the rate of metabolism during exercise in the heat by as much as 3%, indicating that the actual increase in energy requirements for work at high ambient temperatures may vary with the degree of heat acclimation of the individual.

Work in the heat has implications with regard to muscle glycogen synthesis and utilization.[15] Fink et al.[42] found that exercise in the heat increased muscle glycogen utilization, although this has not been observed in all studies.[26,43] Hargreaves[15] speculated that a reduction in muscle blood flow, increased muscle temperature, and elevated catecholamines may contribute to stimulation of muscle glycogenolysis during exercise in the heat. Surprisingly, hypohydration comprising up to 5% body weight loss does not seem to impair muscle glycogen synthesis after exercise.[44] These observations indicate that exercise in the heat may increase glycogen utilization.

Sustained heavy sweat rates increase the loss of sodium and a number of other nutrients, including chloride, potassium, calcium, magnesium, iron, and nitrogen.[36] There is little evidence to suggest these nutrients cannot be replaced adequately by a normal diet.[29] Vitamin supplementation for work in the heat is also unnecessary, with two possible exceptions.[14] Vitamin C has been reported to facilitate heat acclimation,[11] and multiple B vitamins have been reported to lessen fatigue during work in the heat.[12] Generally speaking, vitamin and

mineral supplements will be advantageous only for those with extremely poor dietary habits. Water supplementation during work in the heat is more critical than carbohydrate supplementation.[29] since performance will be impacted sooner by heat and dehydration than muscle glycogen supply. Hence, the provision of water should take precedence over carbohydrate and electrolytes during exercise in the heat,[29] although carbohydrate-containing beverages may be more effective than plain water in the support of continuous exercise lasting longer than 50 min.[27] The key to carbohydrate and water provision during work in the heat is to administer them simultaneously (commercial carbohydrate/electrolyte or "sports" drinks containing 5 to 10% carbohydrate are appropriate). These sports drinks typically contain ~20 meq Na$^+$/l to promote glucose and water absorption from the gut. If it is not feasible to use a carbohydrate/electrolyte drink, concentrate on rehydration with plain water accompanied by adequate food salted a bit more than normal.

Hydration with solutions containing 1 g of glycerol/kg body weight prior to work in the heat may help maintain a better hydration status than plain water alone.[45] This effect is believed to be due to glycerol's hyperhydrating properties. Glycerol seems to provide a fluid reservoir in the interstitial spaces with body tissues. The ingestion of a glycerol solution and water compared to water alone results in decreased urine output, decreased body temperature, increased sweat rate, and lower heart rate during moderate work in the heat.[45] Glycerol-induced hyperhydration appears to be a promising method of reducing the thermal burden during moderate exercise in the heat.

IV. NUTRIENT REQUIREMENTS FOR WORK IN COLD ENVIRONMENTS

Energy requirements are the major consideration for providing nutritional support in a cold environment.[46] Energy expenditure in hot and high-altitude environments is usually limited by the rate of heat buildup and hypoxia, respectively, whereas in a cold environment the rate of energy expenditure is usually not restricted by the heat burden or hypoxia. In addition, high rates of energy expenditure in the cold (~7000 kcal/d) have been attributed to the high degree of motivation of cold-weather expedition team members.[47] Energy requirements in a cold environment are influenced by the intensity of the cold, windspeed, physical difficulties associated with working under winter conditions (preparing shelters, melting snow, locomotion on icy or snow-covered surfaces, etc.) and the light–dark cycle in arctic areas.[48,49] At the same time that energy requirements are high, energy intakes may be reduced by such factors as monotony of the diet and the difficulty of preparing food for consumption under adverse conditions.

Cold exposure increases energy requirements. Most investigators would agree with this statement, but there are several caveats. Johnson and Kark[50] reported that people in a cold climate normally eat more than those in a warm climate. Gray et al.[51] suggested that increased energy requirements were primarily due to a "hobbling" effect of the weight of the clothing and associated inefficiencies of locomotion. Teitlebaum and Goldman[52] subsequently demonstrated that the energy expenditure increase attributable to the weight of arctic clothing (24.6 lbs) was greater than that which could be accounted for by the weight of the clothing alone and attributed it to "friction drag" between the multiple layers of arctic clothing. The weight of cold-weather clothing has decreased as technology has improved; however, clothing is still a considerable burden.

Properly outfitted, modern cold-weather clothing ensembles now weigh 15 to 20 lbs and still account for the major part of the additional energy expenditure in cold not attributed to discernable work such as skiing, snowshoeing, sledging, etc. Mechanical inefficiencies associated with "clothing friction" and "hobbling" combine with small energy requirements to heat and humidify inspired air and air "pumped" into and out of clothing sleeves and seams. These factors contribute to a 10 to 15% increase in the metabolic cost of working in the cold.[40,52,53]

Energy requirements for activities in a cold environment are considerably higher when accompanied by heavy work. However, provided that adequate clothing is worn and allowances are made for the increased weight of the clothing, increases in energy requirements are usually comparable to those for similar activities in a temperate environment.[54,55] (However, energy requirements for an activity may be higher in certain cold environments if the terrain is inefficient for locomotion due to ice or snow.) Cold-weather energy expenditures can range from approximately 3200 kcal/d in low-activity situations to 5000 kcal/d during sledging and manhauling activities.[1] Although considerably higher rates of energy expenditure have been reported,[47] 4500 kcal/d is a reasonable target figure for planning purposes. Recent measurements of U.S. Military cold-weather energy expenditure utilizing the doubly labeled water technique ($D_2{}^{18}O$) confirmed that 4000 to 5000 kcal/d will usually meet cold-weather energy requirements.[56]

The dietary patterns of natives of arctic and subarctic regions and their obvious success in coping with harsh environments have influenced arctic explorers to embrace diets high in fat and led to the general belief that diets high in fat impart a special advantage for work in the cold. Such information is largely anecdotal and probably relates more to the availability of local foods (seal, fish, whale, caribou) and the familiarity of Eskimos with these foods than any real nutritional advantage. Indeed, many Alaskan natives (Eskimos, Indians, and Aleuts) currently consume diets containing 38% of the energy from fat, which is similar to that of the general U.S. population (37%).[57] This change toward lower-fat diets probably reflects the availability of a changing supply of local foods rather than any conscious or unconscious choice influenced by cold weather. Swain et al.[58] reported the caloric consumption distribution pattern of military troops stationed in cold, temperate, nd tropical areas was similar across these environments.

Few studies in the literature deal specifically with nutrient requirements in the cold. These limited studies support the concept that cold does not cause a greater demand for any nutrients other than calories.[50,59,60] Anecdotal reports of "craving" classes of food such as fat or carbohydrate have not been substantiated,[59] yet the idea persists that high-fat diets are especially appopriate for cold-weather operations.

Humans can adapt over a period of time to a high-fat diet[20,61] and much of the submaximal endurance type of work in the cold such as cross-country skiing, snowshoeing, and sledging can be supported by VO_2 max efforts of less than 60%. These moderate sustained power outputs can be supported relatively well by high levels of lipid oxidation.[17,61]

The question next arises: "Does the consumption of a high-fat diet in the cold increase cardiovascular health risk?" It would be irresponsible to recommend a chronically high-fat diet; however, it appears that cardiovascular risk is minimized by the high rate of caloric expenditure associated with work in the cold. An example of this can be seen in the data of Ekstedt et al.[62] (Table 3). Despite consuming a diet containing twice the fat and cholesterol of the low-fat group, cross-country skiers fed the high-fat diet decreased their cholesterol, very-low-density lipoproteins (VLDL), and triglycerides over an 8-d period of cross-country skiing in the cold. The observed decreases were similar to those of the low-fat group and suggests that, in the short run, at least, hard physical work can lessen the normally adverse effect of a high-fat diet on blood lipids.

In addition to the anecdotal, historical, and scientific evidence that high-fat diets are well tolerated in the cold, there is also evidence to suggest that high-fat diets may improve cold tolerance provided that meals are fed at regular intervals during cold exposure[63] (Figure 3).

Despite the arguments that can be made for high-fat diets in the cold, there is evidence suggesting that carbohydrates are more important than fat in fueling metabolic heat production during cold exposure.[21,64] An illustration of this can be seen in Figure 4. Vallerand and Jacobs[64] studied the contribution of protein, carbohydrate, and fat to energy expenditure

TABLE 3 Effect of Low- or High-Fat Diets on
Percent Change of Serum Lipids During Eight
Days Cross-Country Ski Exercise

	Diets[a]	
	Low Fat	High fat
Total cholesterol	-26.4 ± 4.3	-19.9 ± 2.9
VLDL-LDL cholesterol	-38.1 ± 3.0	-41.1 ± 5.7
HDL cholesterol	+5.9 ± 2.3	+19.0 ± 3.8
Triglycerides	-30.6 ± 6.8	-32.6 ± 8.0
Body weight, kg	-0.2 ± 0.5	-0.9 ± 0.4

Note: Data from Ekstedt et al.[a2] $N = 7$, 8-d cross country
ski trip with backpack weighing 30 kg, total distance
covered 160 km.

[a] Low-fat diet, 3800 kcal/d, 26% fat, 260 mg cholesterol
per day; high-fat diet, 3800 kcal/d, 52% fat, 480 mg cho-
lesterol/day. Values shown are mean ± SD of percent
differences before and after ski trip.

EFFECT OF DIET COMPOSITION AND FREQUENCY OF EATING ON COLD TOLERANCE
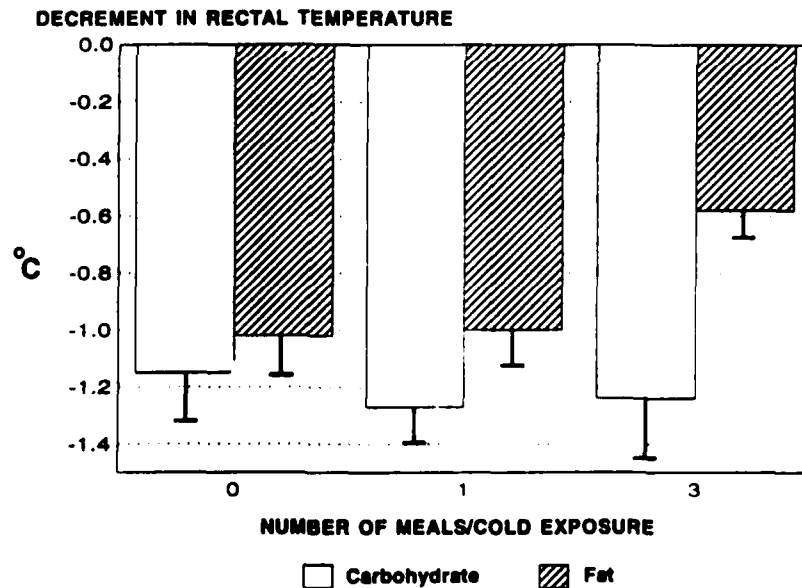
FIGURE 3. The effect of high-carbohydrate (66% of the kcal) or high-fat (73% of the kcal) diets
on cold tolerance (decrease in rectal temperature) during clothed cold exposure at -20°F. The
data for 0 meals was for 6 h of cold exposure; the date for 1 or 3 meals (600 kcal/meal) was
for 8 h of cold exposure. The differences between 0 or 1 meal were not significant. The
differences between carbohydrate and fat for 3 meals was significant ($p < .0001$). (Adapted from
Mitchell, H. H. et al., Am. J. Physiol., 146, 84, 1946. With permission.)

**Influence of cold exposure on
calorie source for resting energy expenditure**
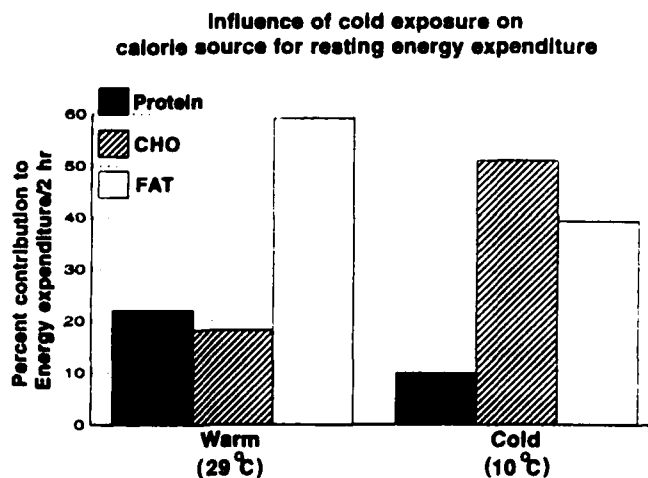
FIGURE 4. Influence of cold exposure on the calorie source for energy expenditure in resting male subjects. Seven subjects were exposed to both warm (29°C) and cold (10°C) conditions for 2 h while they rested (clothed in shorts). Cold exposure induced a body heat debt of 825.9 ± 63.3 kJ, whereas warm exposure produced a heat gain of 92.4 ± 19.2 kJ. Energy expenditure in the cold was 1519.4 ± 150.6 kJ, whereas in the warm it was 617.8 ± 28 kJ. (Data from Vallerand, A. L. and Jacobs, I., *Eur. J. Appl. Physiol.*, 58, 873, 1989. With permission.)

during 2-h exposures of semi-nude men to warm (29°C) or cold (2°C) environments. Cold exposure elevated energy expenditure almost 2.5 times over that observed for subjects in the warm environment. This increase in energy expenditure resulted in an increase in carbohydrate oxidation of 588% and a 63% increase in fat oxidation. Protein oxidation was unaffected. These results demonstrate that cold exposure causes a much greater increase in carbohydrate utilization than lipid. They also suggest that both fat and carbohydrate fuel the shivering response in humans, with carbohydrate (presumably glycogen) being the more important of the two fuel sources. Shivering is impaired by fasting and hypoglycemia.[65,66] Light exercise in the cold results in lower muscle glycogen levels than similar exercise at normal temperature.[67] These observations, coupled with the observation that low muscle glycogen levels are associated with a more rapid body cooling during cold exposure,[68] suggests that muscle glycogen and blood glucose are important, if not critical, fuels for thermogenesis from shivering.[69] Fat can potentially contribute to thermogenesis by fueling the shivering response and/or through triglyceride–fatty acid cycling.[70] The relative importance of these two cycles in humans is not known.[71] Young et al.[71] have reported that metabolic heat production was not significantly affected by dietary lowering of muscle glycogen stores prior to cold exposure, indicating either that fat can adequately fuel cold-induced thermogenesis under reduced muscle glycogen concentrations or that a critical level of muscle glycogen depletion had not been reached. Martineau and Jacobs[72] were unable to alter the thermal responses to cold exposure by simultaneously lowering muscle glycogen and plasma free fatty acids, leading them to suggest that thermal and metabolic responses in the cold can rapidly adjust to compensatory utilization of alternative fuels. Although the lowering of carbohydrate stores does not necessarily result in reduced heat production,[71,72] there is evidence to suggest that a stimulation of carbohydrate oxidation by the ingestion of an ephedrine–caffeine mixture can improve cold tolerance in humans.[73]

Water requirements for work in cold environments are similar to those for temperate environments.[74] Roberts et al.[75] suggested that it is possible to remain adequately hydrated in the cold (at low activity levels) on a minimum of 3 l of water per day. A more generous allowance of 4 to 6 l/d will cover increased fluid requirements for humidifying inspired air

and a certain degree of sweating that may accompany moderate to heavy work levels. Jones[76] reported D_2O-measured turnover rates of 3 to $4\frac{1}{2}$ l/d for U.S. Marines conducting cold-weather training and Edwards et al.[77,78] and King et al.[79] reported water consumption rates of 3.5 to 5 l/d for U.S. Army solders engaged in arctic cold-weather training. Although water requirements are not high in the cold, the consequences of dehydration are still important. Exposure to cold can cause a reduction in the sense of thirst and consequently reduced water consumption.[77,80] This relationship was observed by Edwards and Roberts,[77] who noted that elevated urine specific gravities (>1.030) were associated with the consumption of less than 2 l of water per day by soldiers working in the cold. When forced drinking was initiated, water consumption in these soldiers doubled and urine specific gravities rapidly decreased to the normal range of 1.020. They also found that water consumption and food intake were strongly correlated (r = .76).[77] Dann et al.[80] observed marked voluntary dehydration in a control group during a 4.5-h, 1700-m, cold-weather (0°C) march. The control group exhibited evidence of dehydration, decreased glomerular filtration rate, osmotic clearance, and urine volume compared to the imposed drinking discipline group. Dann et al.[80] calculated that a fluid intake of 150 ml/h during exercise in the cold would be required to maintain a urinary flow rate of about 1 ml/kg/h necessary for a good state of hydration.

Hypohydration in the cold can reduce food consumption, efficiency of physical and mental performance and resistance to cold exposure.[81] While adequate fluid intake is paramount in preventing hypohydration in the cold, it is also prudent to consider the temperature of fluid and food provided for work in the cold. Warm fluids and heated foods are generally recommended in the cold, whenever possible, to impart a feeling of warmth and well-being.[81] The warming effect of a hot beverage in the cold is probably related to its effect upon subsequent vasodilation and increased blood flow to cold extremities rather than to the actual quantity of heat contained in the ingested fluid. Wilson and Culik[82] have provided the thought-provoking suggestion that the real advantage to providing warm food in the cold is the net heat savings that results to the body compared to ingesting ambient temperature (cold) food. Their calorimetric calculations based upon observations conducted with penguins fed warm or cold krill (fish) suggest that up to 13% of the daily energy expenditure of the penguin may be devoted to heating cold ingested food to body temperature. The lesson for human sojourners in the cold is apparent and can probably be taken to heart even in the absence of similar human studies.

It is clear that in a cold environment, man must adapt his behavior to minimize cold exposure and achieve homeothermy; failure to do so will result in rapid performance decrements and even death. The energy costs of performing any task under extreme cold conditions is higher than performing the same task under temperate conditions because of the difficulties in working in heavy clothing and traveling in snow. Working in cold environments does not lead to an increased requirement for any nutrient other than energy. Carbohydrate intake may be of concern if high power output (>50% VO_2 max) is required for extended periods of time. Replenishment of muscle glycogen stores will assure the availability of this fuel during exercise and shivering to support thermogenesis and aid the body in fighting hypothermia. Caloric demands for moderate to high activity levels in arctic and subarctic areas are usually adequately supported by 4000 to 5000 kcal/d.

Weight loss is common during cold-weather field expeditions, often due to the monotony of the diet and difficulty in preparing food, coupled with increased energy expenditures. Water requirements are not increased in cold-weather operations, but intakes may be decreased due to the difficulty of melting snow and ice and the tendency of cold weather travelers to utilize dry foods that will not freeze and can be eaten without thawing. Inadequate hydration may decrease the body's ability to adjust to cold stress.

V. NUTRIENT REQUIREMENTS FOR WORK AT HIGH ALTITUDE

Abrupt exposure to altitudes greater than 10,000 ft (3050 m) elevation is frequently associated with symptoms of altitude sickness.[83] Altitude sickness is a generalized term referring to a combination of symptoms, including headaches, anorexia, nausea, vomiting, and malaise. The experienced mountaineer knows that gradual acclimation to progressively higher altitude exposure is the best preventive medicine for high-altitude sickness.[84,85] Gradual ascent over a period of days from sea level to high altitude is accompanied by a number of simultaneous physiologic adaptations that permit the accomplishment of significant work with minimal physical symptoms other than an increased perceived exertion. Unfortunately, it is not always practical or possible to delay ascent to altitude. Soldiers and rescue workers frequently must travel abruptly to high altitudes to perform critical missions. Prior acclimation is not possible. Abrupt transportation from sea level to high altitude is usually accompanied by debilitating altitude sickness influencing symptoms, mood, and performance.[85,86] These uncomfortable symptoms usually increase in intensity for periods of up to 48 h after altitude exposure and then gradually lessen.[87] Unfortunately, it is usually during the first 48 h at altitude that critical work must be accomplished. Although there is some debate as to whether altitude exposure causes an absolute increase in energy requirements above that of similar work performed at sea level,[55,88] the usual activities associated with missions at altitude and the lack of adequate food intakes almost invariably result in an initially negative energy balance.[89-91] Altitude exposure (and the accompanying hypoxia) is associated with a 17 to 27% increase in basal metabolic rate which raises energy requirements above sea level.[92] However, altitude exposure is often accompanied by a decrease in voluntary energy expenditure which may cancel the new effect of an increase in basal metabolic rate.[92] Energy expenditures in experienced and motivated climbers can be quite high[90] and depend upon the activity level.

Rose et al.[93] observed depressed food intakes and weight loss at altitude even under the chamber conditions of Operation Everest II. In this study, work requirements were relatively low and a thermoneutral hypobaric environment with an adequate quantity and variety of palatable food was provided. Reduced food intake under these conditions indicated that hypoxia by itself was a major factor reducing appetite and food intake. Adequate food intake can be achieved at altitude but it requires a concerted conscious effort of dietary management and forced eating.[92] The usual combination of anorexia and reduced food intake can potentially exert a negative effect on work performance at even moderate altitude.[55] Food intakes are usually reduced 10 to 50% during acute altitude exposure.

Numerous pharmacological attempts to reduce acute mountain sickness have been investigated, with limited success. High-carbohydrate diets have been recommended as a "non-pharmacological" method to reduce the symptoms associated with acute mountain sickness.[1] To be effective, these diets should be fed prior to and during the initial 3- to 4-d critical period of acute altitude exposure. It should be noted that only a limited number of investigators have studied high-carbohydrate diets or carbohydrate supplements for the relief of acute mountain sickness and performance enhancement. Most, but not all, have reported some beneficial effects upon symptoms, mood, and performance. Consolazio et al.[94] conducted a study at 14,000 ft elevation with two groups of young sea level natives transported abruptly to altitude. One group consumed a normal diet containing 35% of the calories in the form of carbohydrate. The second group consumed a diet containing approximately 70% of the calories from carbohydrate. The normal carbohydrate group was more nauseated, less energetic, and more depressed than the group consuming the high-carbohydrate diet. The normal carbohydrate group also experienced greater heart pounding, was more irritable, more tired, and less happy than the high carbohydrate group. They also felt less lively and experienced greater shortness of breath. Both groups experienced dizziness, cramping, head-

aches, and trouble sleeping to approximately the same degree. Work performance was compared in a relatively high-exertion, short-duration protocol consisting of walking on a treadmill at 3.5 mph on an 8% grade carrying a 20-kg pack. During the sea level control period all men completed the 15-min walk but at altitude, the normal carbohydrate group averaged only 4.5 min, while the high-carbohydrate group averaged 9.8 min until exhaustion. Askew et al.[89] studied exercise at high altitude under conditions designed to stress muscle glycogen stores. They abruptly transported three groups of soldiers from sea level to 4100 m (13,500 ft) elevation (summit of Mauna Kea, Hawaii). One group of solders remained sedentary and consumed a normal military field ration (45% carbohydrate) during 4 d at this elevation. The other two groups were paired according to their $\dot{V}O_2$ max determined at sea level and exercised for 2 h/d at altitude by running on a cross-country course at an exertion level of 70% of their maximum heart rate. One of the exercise groups consumed the same 45% carbohydrate ration as the sedentary group. The other exercise group consumed the same basal diet as the other two groups but received approximately 200 g of carbohydrate supplement per day through glucose polymer-supplemented beverages (approximately 40 g of carbohydrate per 8-oz beverage). The nonsupplemented groups consumed similar beverages sweetened with a non-nutritive sweetener. All beverages were provided *ad libitum*. The nonsupplemented group consumed an average of 190 g of carbohydrate per day, whereas the group receiving the carbohydrate supplement consumed an average of 400 g of carbohydrate per day during the 4 d at altitude. Total voluntary mileage covered during the 2 h/d running period was recorded daily. The carbohydrate-supplemented group logged a significantly greater ($p < .05$) 12% total miles covered over the course of this 4-d study. In addition to improving energy balance, carbohydrate supplementation also improved nitrogen balance in the initial phase of acute altitude exposure. Butterfield et al.[92] have confirmed that the negative nitrogen balances encountered at altitude is not due to any decrease in protein digestibility or absorption, but primarily due to negative energy balances.

The exact mechanism by which carbohydrate exerts a beneficial effect on relieving symptoms of altitude sickness and prolongs endurance at altitude is not known. Hansen et al.[95] showed that blood oxygen tension is increased by a high-carbohydrate diet and Dramise et al.[96] reported that carbohydrate can increase lung pulmonary diffusion capacity at altitude. The energy production per liter of oxygen uptake is greater when carbohydrate is the energy source compared to fat (carbohydrate, 5.05 kcal/l O_2; fat, 4.69 kcal/l O_2) regardless of the oxygen tension in the inspired air.[97] Taken together, these different lines of evidence suggest that carbohydrate is a more efficient energy source for work at reduced oxygen tension.[98] The beneficial effect of high-carbohydrate diets on physical performance at sea level is well known.[9] Carbohydrate can prolong endurance by its effect on muscle glycogen stores which are in turn closely related to endurance. It is unlikely that the ergogenic effect of the high-carbohydrate diets at altitude reported by Consolazio et al.[94] was related to a specific muscle glycogen effect, since the short exercise time periods (<10 min) should not have been limited by glycogen stores, but may have been related to the provision of blood glucose to the working hypoxic muscles. Caffeine has also been reported to enhance relatively short-term, high-intensity work at simulated high altitude,[99] perhaps via a similar influence upon blood glucose availability.

There is little evidence that chronic or acute altitude exposure increases the requirement for any specific nutrient[100] other than possibly vitamin E[10] and iron.[13] Some workers have noted that supplementation of vitamins having an antioxidant function may be desirable at high altitude.[10,14,101] Simon-Schnass[10] reported that supplemental vitamin E (2 × 200 mg daily) during a prolonged stay at high altitude prevented a "deterioration" of blood flow and a decrease in physical performance associated with free radical damage to cellular antioxidant defense systems. Simon-Schnass[10] theorized that the "oxidative stress" during

**Calculated 24 hour water respiratory loss during
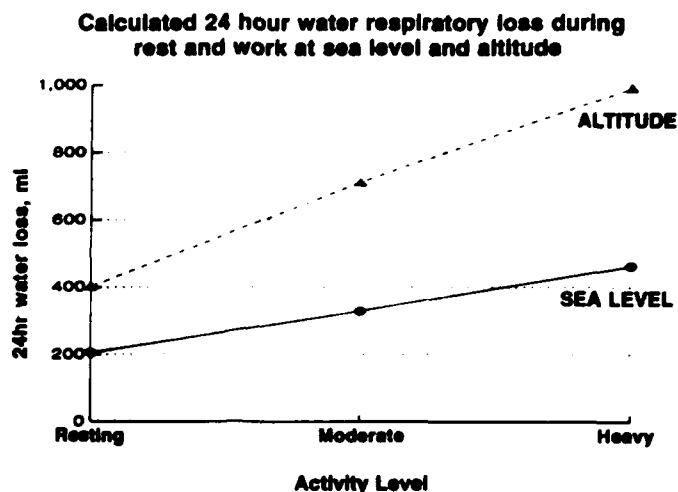rest and work at sea level and altitude**

FIGURE 5. Calculation of 24-h respiratory water loss at three activity levels at sea level and at altitude. Resting and moderate estimations are at sea level and 5570 m. The estimation for heavy activity is at sea level (hill walking) and ~8000 m (climbing). Detailed information on the equations and assumptions involved in the calculation of these values can be found in Milledge, J., *Newsletter of the International Society for Mountain Medicine,* 2, 5, 1992. (After Milledge,[103] with permission.)

hypoxia is a consequence of alterations in the oxidation–reduction potential leading to lipid peroxidation and free radical production and subsequent oxidative injury to tissue and blood.

The suggestion that supplementary dietary iron may be beneficial at altitude stems from the observation that there is an increased erythropoietic response to altitude exposure as the oxygen delivery system of the blood attempts to support increased hemoglobin synthesis at high altitude.[83] Although Hornbein[102] concluded that normal dietary iron intakes are adequate to support increased hemoglobin synthesis for males at high altitude, Hannon[13] suggested that females exposed to high altitude may benefit from a dietary iron supplement.

Water requirements at altitude may be greater than those at sea level, due to the low humidity of the atmosphere at altitude and hyperventilation associated with altitude exposure.[13,55,98] Normal water consumption and normal to slightly reduced urine outputs at altitude (compared to sea level) can still lead to dehydration when accompanied by an increased rate of insensible water loss. The risk of dehydration is high at altitude due to water loss in breath and sweat coupled with the difficulty of obtaining adequate water.[103] Based upon the equations and assumptions of Ferrus et al.,[104] Milledge[103] has estimated that the rate of respiratory water loss is probably less than 1 l/d. This is still about twice the rate of respiratory water loss for an equivalent activity at sea level. Milledge[103] has calculated theoretical 24-h respiratory water loss at rest and at work at sea level and at high altitude. These predictions are shown in Figure 5.

An inappropriate thirst response coupled with an increase in insensible water loss and a transient diuresis during the initial hours of altitude exposure, can result in rapid dehydration if adequate fluid is either unavailable or neglected.[105]

High altitude and cold environments are often similar with respect to the thermal challenge, tempting one to categorize work in snow and cold at sea level with work under similar conditions at altitude. There are some distinct differences which should be considered when planning nutritional support at high altitude. Fat, while tolerated relatively well in the cold at sea level, may not be as well tolerated in diets at high altitude. The symptoms of acute altitude exposure may worsen, especially if fat displaces carbohydrate from the diet. Although high-fat foods are energy dense and reduce the weight/calorie aspect of food carried on

TABLE 4 Generalized Influence of Environment upon Nutrient Utilization

Utilization	Environment		
	Heat	Cold	Altitude
Dietary tolerance			
Carbohydrate	+	0	+
Fat	–	+	–
Protein	–	0	0
Metabolism			
Carbohydrate	+	+	+
Fat	0	+	–
Protein	0	0	0
Performance			
Carbohydrate	+[a]	+	+
Fat	–	0, +	–
Protein	–	0	0

Note: These generalizations are qualitative in nature and are drawn from the literature reviewed in this chapter. As with all generalizations, there are exceptions. A (+) indicates an augmentation, (–) a diminishment, and (0) is no change.

[a] The enhancement of performance by carbohydrate in the heat assumes adequate water.

climbs, fat requires more oxygen for metabolism than carbohydrate and will place a small, but added, burden upon the already overtaxed oxygen economy of the climber. Fat absorption may also be reduced as the climber exceeds elevations above 6300 m;[106] however, elevations commonly reached by recreational skiers, snowshoers, and backpackers are usually not associated with impaired fat absorption.[92] One other difference between cold exposure at sea level and high altitude is the calorigenic response to cold. Cold exposure during hypoxia results in an increased reliance upon shivering for thermogenesis due to a reduction in nonshivering thermogenesis at altitude.[107,108] Robinson and Haymes[108] suggested that this is due to a reduction in aerobic catabolism of free fatty acids during hypoxia.

Inappropriate thirst and appetite responses, together with increased insensible water loss, transient diuresis, and increased energy expenditures, can lead to rapid dehydration and glycogen depletion if adequate food and fluid is neglected. Dehydration may intensify the symptoms of altitude sickness and result in even lower food intakes. One of the most effective and practical performance-sustaining measures that can be adopted upon arrival at high altitude is to consume a minimum of 3 to 4 l of fluid per day containing 200 to 300 g of carbohydrate in addition to that contained in the diet. This should prevent dehydration, improve energy balance, improve the oxygen delivery capability of the circulatory system, replenish muscle glycogen, and conserve body protein levels.

VI. SUMMARY

A generalized summary of the influence of environment upon nutrient utilization is depicted in Table 4. The challenge of providing adequate nutrition in environmental extremes is one of furnishing a palatable diet generally high in carbohydrate to meet high energy demands. Adequate fluid replacement is critical in any environment. Dehydration can reduce appetite and compromise thermoregulation. Practical dietary recommendations can be made

TABLE 5 Do's and Don'ts for Recreational and Expedition Meal Planning

DO provide group/hot meals whenever possible. People will generally eat more when warm meals are consumed "socially".	DON'T assume that everyone is eating adequately in group feeding situations. A meal prepared is not necessarily a meal eaten.
DO schedule breaks for meals and snacks even when individual food will be consumed for the meal or snack. Left to their own initiative people will frequently skip or shorten meals to accomplish tasks they feel are more "important".	DON'T allow snack food to substitute for meals. Snacks should augment or supplement daily meals, primarily as a means to increase total daily energy or carbohydrate intake. Snacks should be a morale and performance booster, not an obsession.
DO observe what food items are being consumed. Picky dietary habits can lead to imbalances of vitamins, minerals, or energy. Vitamin and mineral supplements are usually not needed; a multivitamin supplement can provide some "insurance" for finicky eaters.	DON'T permit individuals to use the expedition as a "crash" weight loss program. Dehydrated, ketotic, and weak team members jeopardize the safety of others as well as themselves.
DO encourage water consumption with meals. Meal time is often a major fluid consumption point due to the opportunity to prepare beverages, soups, and other water-containing food items.	DON'T permit food and personal hygiene to slip just because you are in the field. Clean hands, clean utensils, and disinfected water are requisite for safe food preparation.

to optimize performance in environmental extremes. Some practical guidelines for recreational or expedition meal planning in environmental extremes are shown in Table 5. Proper nutrition can prevent or minimize performance decrements that often accompany environmental stress and help to make a "hostile" environment a bit less "hostile".

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